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# IN-SITU FEEDER PIPE GAMMA SPECTROMETRY IN SUPPORT OF PNGS UNIT 3 DECONTAMINATION

Report No. 89-256-K

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## ABSTRACT

The activity of feeder pipes was measured using a newly developed in-situ gamma spectrometry technique. Measurements were made at various stages of the recent 3-step decontamination of PNGS Unit 3. Using calculated conversion factors, contact pipe fields corresponding to measured radioisotope activities were deduced and compared with measured shielded pipe radiation fields. The agreement was very encouraging.

Examination of the data revealed that Sb-124 was deposited on the carbon steel piping during the 1st reducing step (CAN-DECON); a small proportion of the deposited antimony was subsequently removed in the final reducing step. The intermediate oxidizing step (alkaline permanganate) itself was ineffective in mobilizing the deposited antimony; this observation is in accord with previous laboratory experience using contaminated CS coupons.



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## EXECUTIVE SUMMARY

# IN-SITU FEEDER PIPE GAMMA SPECTROMETRY IN SUPPORT OF PNGS UNIT 3 DECONTAMINATION

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A three-step decontamination of PNGS Unit 3 was performed in June-August '89 in preparation for its retubing. The first step, a CAN-DECON treatment, was applied in June following partial defuelling of the reactor core; the second step, an oxidizing dilute alkaline permanganate treatment and the final CAN-DECON step were successively applied in August '89 after complete removal of fuel from the reactor core.

Gamma spectrometry of various primary heat transport system (PHTS) components was performed in support of the decontamination. Included were scans of two outlet and two inlet feeder pipes located inside the West Feeder Cabinet. A recently developed technique was used to convert measured counts into radioisotope activity. The information was required by CPSD to determine the contribution of feeders to vault radiation fields. Measurements were made at various stages of the 3-step decontamination. The results of the feeder pipe scans are described in this report while those for other components are described elsewhere.

The feeder pipes selected for measurement were P1 (outlet, S. Loop), T18 (inlet, S. Loop), P21 (outlet, N. Loop) and U5 (inlet, S. Loop). The accessible length of each pipe was limited by the height of the feeder cabinet (~4 ft.). While the spectrometer during measurement was placed on the walkway adjacent to these pipes and viewed their lower portions, gamma survey detectors housed within annular lead shields installed on the upper portion of the pipes provided contact pipe field measurements. The shielded gamma survey detectors were installed by CPSD to remotely monitor field reductions during the decontamination and as a spin-off provided valuable data for assessing the validity of measured pipe activities.

To validate the technique, contact pipe fields corresponding to measured radioisotope activities were deduced using calculated conversion factors. These were then compared with measured shielded pipe radiation fields. The agreement was very encouraging with the measured fields on average being ~75% of the calculated fields. Sources of error were identified and steps to minimize their effect are discussed.



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Examination of the data revealed that Sb-124 was deposited on the carbon steel (CS) piping during the 1st reducing step (CAN-DECON); a small proportion of the deposited antimony was subsequently removed in the final reducing step. The intermediate oxidizing step (alkaline permanganate) itself was ineffective in mobilizing the deposited antimony; this observation is in accord with previous laboratory experience using contaminated CS coupons. This behaviour warrants a re-examination of process options should Sb-124 removal be crucial in future decontaminations.

It is recommended for greater ease in performing measurements and to minimize man-rem expenditure that suitability of alternative locations such as at the reactor face or inside the vertical feeder cabinets be assessed.

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To Mr. R.W. Patterson
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# IN-SITU FEEDER PIPE GAMMA SPECTROMETRY IN SUPPORT OF PNGS UNIT 3 DECONTAMINATION

## 1.0 BACKGROUND AND INTRODUCTION

A three-step decontamination of PNGS Unit 3 was performed in June-August '89 in preparation for its retubing. The first step, a CAN-DECON treatment, was applied in June following partial defuelling of the reactor core; the second step, an oxidizing dilute alkaline permanganate treatment and the final CAN-DECON step were successively applied in August '89 after complete removal of fuel from the reactor core.

Gamma spectrometry of various primary heat transport system (PHTS) components was performed in support of the decontamination. Included were scans of two outlet and two inlet feeder pipes located in the West Feeder Cabinet. A recently developed technique/1/ was used to convert measured counts into radioisotope activity. The information was needed to estimate the specific activity of the oxide (this allows the progress of the decontamination to be monitored) and to determine the contribution of feeders to vault radiation fields. Measurements were performed before and after the 1st CAN-DECON step, prior to the oxidizing step and following the last CAN-DECON step. The results of the feeder pipe scans are described in this report while those for other components are described elsewhere.

The feeder pipes selected for measurement were P1 (outlet, S. Loop), T18 (inlet, S. Loop), P21 (outlet, N. Loop) and U5 (inlet, S. Loop). The accessible length of each pipe was limited by the height of the feeder cabinet (~4 ft.). While the spectrometer during measurement was placed on the walkway adjacent to these pipes and viewed their lower portions, gamma survey detectors housed within annular lead shields installed on the upper portion of the pipes provided contact pipe field measurements. The shielded gamma survey detectors were installed by CPSD to remotely monitor field reductions during the decontamination and as a spin-off provided valuable data for assessing the validity of measured pipe activities.

Determination of pipe activity involves aligning a shielded, collimated gamma spectrometer system perpendicular to the pipe's axis and performing two measurements. In the first measurement, the spectrometer system registers the signal counts superimposed on a general background count while during the second measurement, the opening in the collimator is plugged with a cylindrical rod to enable the recording of background counts only. The difference in the two measured counts is converted into activity using an efficiency curve. Previous evaluation of the technique using active feeder pipe sections yielded results which were up to 30% higher than expected. Although the results of field assessment appeared to be satisfactory, no direct validation of the data was performed.

In earlier work, an annular shield made from uranium metal was used for housing the snout of the spectrometer. The central bore of the shield was fitted with a Densalloy sleeve to minimize the interference in the spectra from uranium daughter decay peaks. This was not very satisfactory and hence prior to undertaking the present measurements, a spectrometer shield along with collimators, plugs and a pipe shield (to minimize entry of radiation from behind the pipe) fabricated entirely from Densalloy were procured from Teledyne (see Appendix for shield details).

This report describes briefly the pipe source calibration procedures undertaken, interpretation of spectral results, assesses the validity of measured activities and briefly examines the significance of the data in the context of the decontamination.

## 2.0 PIPE SOURCE EFFICIENCY CALIBRATION

Pipe source efficiency calibrations were developed prior to undertaking the field measurements to enable timely interpretation of the data. A water-filled pipe source was simulated using a source sheet as previously described/1/. The source sheet had a deposited activity of 369 ± 26 nCi/cm$^2$ Co-60 and 413 ± 29 nCi/cm$^2$ Cs-137. Two pipes, with dimensions similar to the outlet and inlet feeders, respectively, were calibrated.

Measured pipe efficiencies along with values calculated for a pipe-collimator face distance of zero are shown in Figures 1 & 2. The calculations, performed for completeness, are based on a parallel plate approximation/1/ and are valid over the short distance range indicated in the plots. Point source efficiency data and attenuation coefficients for Densalloy/2/ required to perform the calculations are given in the Appendix.

An alternate representation of the pipe source efficiency data is shown in Figures 3 and 4 where efficiency is plotted versus photon energy on a log-log plot. The linearity (also observed previously/1/ over a much wider energy range) of the plots was used to interpolate/extrapolate pipe efficiency data (at any distance) to photon energies corresponding to observed isotopes in the feeder pipe spectra.

## 3.0 THE EXPERIMENTAL SITUATION

Radiation fields within the feeder cabinet before decontamination varied from ~150 mR/h along the outlet header to ~1500 mR/h along the inlet header. The two outlet feeders selected were in front of the North and South door entrances to the feeder cabinet. While equipment set-up at these locations did not present much difficulty, the narrow walkway and insufficient headroom combined with the high radiation fields along the inlet header made equipment set-up and alignment a very formidable task.

Following the first set of measurements, performed on P21, it was evident that excessive manipulation would be required to align the circular pipe shield with the axis of the collimator. To minimize undue radiation exposure, it was decided for all subsequent measurements to replace the circular pipe shield with two lead blankets slung together. Because of the relatively large size of the blankets, alignment was not of particular concern. However, due to the lower combined thickness (~1 cm) of the two lead blankets and the smaller attenuation coefficient of lead (compared with the two inch thickness of the Densalloy pipe shield) extraneous radiation from behind the pipe may possibly have entered the detector leading to somewhat inflated signal counts.

Connections between the detector and the multi-channel analyser (MCA) located outside the reactor vault were via the junction box located in the boiler room. It is probable that the long cable required may have caused some loss of signal particularly for the low energy peaks in the spectrum. This was indeed observed to be the case for reactor face gamma scans - those recorded on a portable Series 30 MCA indicated additional low energy peaks which were not observed using the remotely located Series 35 MCA.

## 4.0 RESULTS AND DISCUSSION

Data for all pipe scans performed are summarized in the Appendix. A typical analysis of the feeder pipe data is illustrated in Table 1. Net counts were determined for all observed peaks and only those with a relative error (2σ) less than 50% were considered to be significant. Thus for the case in Table 1, Co-60 and Nb-95 were the only significant isotopes detected. Their efficiencies

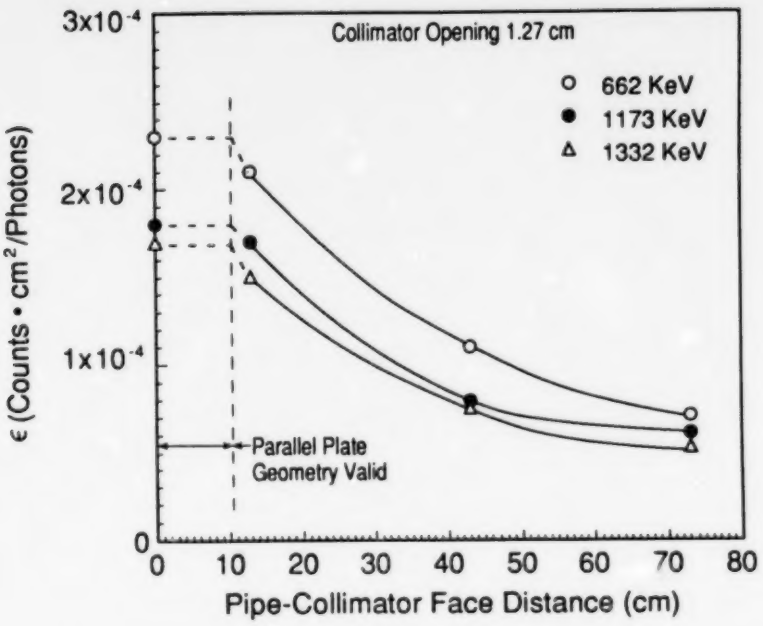


**Figure 1. Efficiency Curve for Pipe With OD 7.68 cm(3.06") & ID 6.27 cm (2.478")**

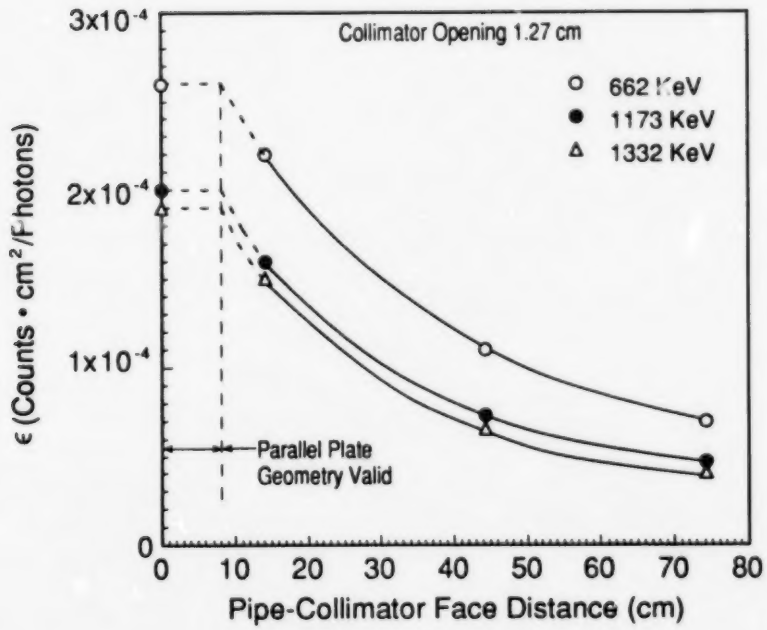


**Figure 2. Efficiency Curve for Pipe With OD 6.1 cm (2.40") & ID 5.0 cm (1.969")**

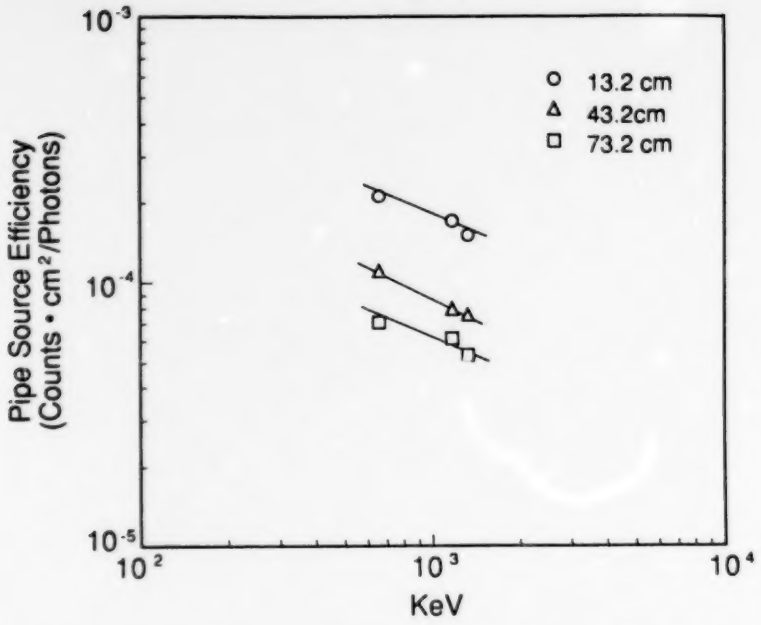


**Figure 3. Variation of Pipe Source Efficiency with Photon Energy for Pipe with OD 7.68 cm (3.06") & ID 6.27 cm (2.478")**

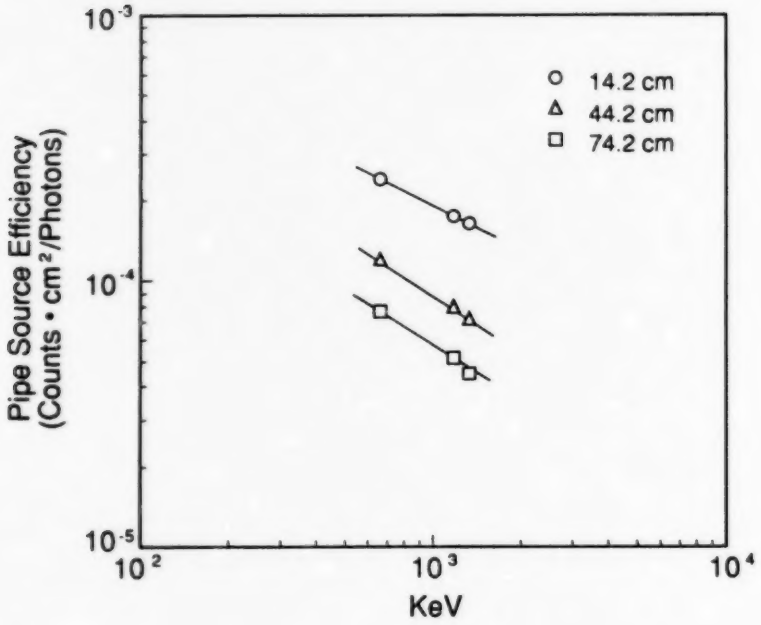


**Figure 4. Variation of Pipe Source Efficiency with Photon Energy for Pipe with OD 6.10 cm (2.40") & ID 5.0 cm (1.969")**

## TABLE 1

## TYPICAL ANALYSIS OF FEEDER PIPE DATA

Feeder Pipe: U5 (Inlet)
Collimator Opening: 1.27 cm
Pipe-Collimator Face Distance: 41 cm

| Isotope | Kev | Counts / sec (CPS) Plug Out* | Plug In* | Net+ | | Pipe Eff. (Counts.cm$^2$ /Photons) | Activity** (mCi/m$^2$) |
|---|---|---|---|---|---|---|---|
| Zr-95 | 724.2 | 0.690 ± 0.308 | 0.005 ± 0.290 | 0.685 ± 0.414 | (60.4%) | - | - |
| Zr-95 | 756.7 | 0.862 ± 0.322 | 0.073 ± 0.300 | 0.790 ± 0.431 | (54.6%) | - | - |
| Nb-95 | 765.8 | 3.168 ± 0.318 | 0.439 ± 0.282 | 2.728 ± 0.418 | (15.3%) | 1.13 E-4 | 6.6 |
| Mn-54 | 834.8 | 0.448 ± 0.278 | 0.124 ± 0.260 | 0.324 ± 0.372 | (114.8%) | - | - |
| Fe-59 | 1099.2 | 0.439 ± 0.248 | 0.165 ± 0.216 | 0.274 ± 0.322 | (117.5%) | - | - |
| Co-60 | 1173.2 | 19.080 ± 0.286 | 8.991 ± 0.228 | 10.090 ± 0.359 | (3.6%) | 0.85 E-4 | 32.1 |
| Fe-59 | 1291.6 | 0.372 ± 0.084 | 0.245 ± 0.080 | 0.127 ± 0.113 | (89.0%) | - | - |
| Co-60 | 1332.5 | 20.265 ± 0.262 | 11.488 ± 0.218 | 8.777 ± 0.334 | (3.8%) | 0.75 E-4 | 31.6 |
| La-140 | 1596.5 | 0.529 ± 0.052 | 0.426 ± 0.048 | 0.103 ± 0.069 | (67.0%) | - | - |
| Sb-124 | 1691.0 | 0.102 ± 0.032 | 0.098 ± 0.028 | 0.004 ± 0.041 | (1025.0%) | - | - |

* The counting error (2σ) was calculated using the formula √(Background counts/s+ Gross counts/s).
\+ Overall counting error was calculated using the formula $2\sqrt{(\sigma^2_{out} + \sigma_{in}^2)}$. Figures in brackets indicate the relative error.
** mCi/m$^2$ = (cps/Pipe Eff.) / (3700 A) where A is the fractional abundance of the peak.

corresponding to a pipe-collimator distance of 41 cm were determined from Figures 1 & 2 as described earlier. As expected, essentially identical activities were measured for both Co-60 emissions.

The activities of significant isotopes on each pipe at various stages of the decontamination are summarized in Table 2. Activities corresponding to dual peak emissions of an isotope were generally averaged; in a few cases the value selected corresponded to the peak with a significantly lower error on the net counts.

Measured and estimated fields for each pipe are also listed in Table 2. Estimations were based on conversion factors shown in Table 3. These were calculated/3/ assuming the gamma survey detector to be located at a distance of 0.75 cm from the pipe's OD. Note that the conversion factors for the larger pipe, instead of being greater, are essentially similar to those for the smaller pipe. Evidently this is due to the closer proximity of the gamma survey detector to the ID of the smaller pipe.

Coolant activity was considered negligible in interpreting spectral data. The effect of coolant activity on pipe fields was estimated to be 23 and 18 mR/h per 100 μCi/l Co-60 for the inlet and outlet feeders respectively/3/. The prevailing coolant activity during all measurements was <0.1 μCi/l (measurements following each CAN-DECON were made several hours after the mixed bed clean-up had been in effect). Thus, even after the 3-step decontamination, the relative contribution of coolant activity to pipe fields and spectral measurements was negligible.

4.1 Validity of Measured Activities

Agreement between measured and calculated radiation fields varied from essentially complete agreement in two cases to less than 50% in the case of the P21 measurement before CAN-DECON. For the remaining cases, the agreement on average was ~75%. Considering the difficulties in performing the measurements, this outcome is considered to be very encouraging. Itemized below are the various sources of experimental error:

1. Insufficient or misaligned shielding behind the pipe during spectrometry would inflate the values for the measured activity and hence increase the discrepancy between measured and calculated radiation fields.

2. The effect of uncertainty in the exact location of the gamma survey detectors within their lead shields is illustrated in Figure 5. The detector may possibly have been further from the pipe's surface than assumed (0.75 cm). Hence, the conversion factors given in Table 3 are somewhat exaggerated and would cause calculated fields to be higher.

3. The theory based on which conversion factors were calculated inherently overestimates their values by 10-20%/4/.

4. The energy response/5/ of the gamma survey detector (LND 714) with its original compensating filters is shown in Table 4. A very non-uniform energy response is evident -- the significantly higher response to Co-60 radiation compared to Cs-137 radiation is possibly due to scatter arising in the compensating filters. While the response at energies less than 662 keV would offset the over-response at energies greater than 662 keV, it is probable that under the conditions of measurement (most of the activity was due to isotopes with emissions greater than 662 keV), the radiation fields measured were greater than the actual fields.

5. Loss of signal particularly for lower emitting isotopes due to extended length of cable between detector and MCA, and

6. A random error due to pipe efficiency calibration procedure.

The effect of Items 1-3, offset to some extent by that of Items 4 and 5 may possibly explain why the measured fields were lower than those calculated.

## TABLE 2

## MEASURED ACTIVITY (mCi/m²) OF FEEDER PIPES AT VARIOUS STAGES OF DECONTAMINATION

| ISOTOPE | Outlet Feeder P21 | | | | Outlet Feeder P1 | | | | Inlet Feeder U5 | | | | Inlet Feeder T18 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Before R | After R | Before O* | After ROR | Before R | After R | Before O | After ROR | Before R | After R | Before O | After ROR | Before R | After R | Before O* | After ROR |
| Ru-103 | 3.00 | 0.64 | | - | - | 1.23 | - | - | - | | - | - | 2.49 | - | | - |
| Zr-95 | 1.46 | - | | - | 1.80 | - | - | - | - | | - | - | - | - | | - |
| Nb-95 | 2.41 | - | | - | 2.68 | - | - | - | 6.60 | | 1.55 | - | 4.90 | - | | - |
| Fe-59 | 0.89 | - | | - | 0.79 | - | - | - | - | | - | - | 1.86 | - | | - |
| Co-60 | 6.93 | 2.65 | | 0.55 | 5.36 | 3.00 | 4.75 | 1.10 | 31.90 | | 7.10 | 0.97 | 56.60 | 1.51 | | 0.84 |
| La-140 | 0.30 | - | | - | 0.54 | - | - | - | - | | - | - | 0.72 | - | | - |
| Sb-124 | 0.46 | 3.16 | | 0.95 | 0.27 | 2.75 | 0.97 | 0.72 | - | | 1.45 | 1.00 | 0.48 | 1.67 | | 1.21 |
| MEASURED FIELD (mR/h) | 62.0 | a | 50.0 | 13.0 | 72.0 | 50.0 | 55.0 | 19.0 | 460.0 | 76.0 | 90.0 | 15.0 | 525.0 | 37.0 | 40.0 | 19.0 |
| CALCULATED FIELD (mR/h) | 138.5 | 67.6 | | 16.3 | 109.8 | 70.7 | 73.6 | 21.6 | 478.1 | | 120.5 | 22.9 | 847.8 | 36.7 | | 23.1 |
| MEAS.F/CALC. F(%) | 44.8 | - | | 80.0 | 65.5 | 70.8 | 74.8 | 87.9 | 96.2 | | 74.7 | 65.5 | 61.9 | 100.8 | | 82.4 |

a Equipment malfunction - field could not be measured.

* Spectrometer was probably incorrectly aligned. Net counts measured with 1.27 cm. and 1.91 cm. collimators were mutually inconsistent.

\+ Spectra was not acquired.

**TABLE 3**

**FACTORS FOR CONVERTING PIPE SURFACE ACTIVITY TO CONTACT RADIATION FIELDS*/3/**

| Isotope | Outlet Feeder | Inlet Feeder |
|---|---|---|
| Ru-103 | 3.62 | 3.79 |
| Zr-95 | 4.95 | 5.08 |
| Nb-95 | 5.11 | 5.25 |
| Mn-54 | 5.27 | 5.40 |
| Fe-59 | 6.59 | 6.73 |
| Co-60 | 13.60 | 13.90 |
| La-140 | 12.30 | 12.30 |
| Sb-124 | 9.24 | 9.41 |

* Detector located 0.75 cm from outer pipe surface.

**TABLE 4**

**ENERGY RESPONSE OF GAMMA SURVEY DETECTOR/5/**

| Photon Energy (keV) | Normalized* Energy Response | |
|---|---|---|
| | Frontal Exposure | Side Exposure |
| 47 | 0.16 | 0.45 |
| 59 | 0.52 | 0.56 |
| 85 | 1.21 | 0.60 |
| 107 | 0.78 | 0.45 |
| 147 | 0.99 | 0.39 |
| 183 | 1.01 | 0.48 |
| 210 | 0.92 | 0.52 |
| 662 (Cs-137) | 1.00 | 1.00 |
| 1250 (Co-60) | 1.58 | 1.52 |

*With respect to Cs-137 response.

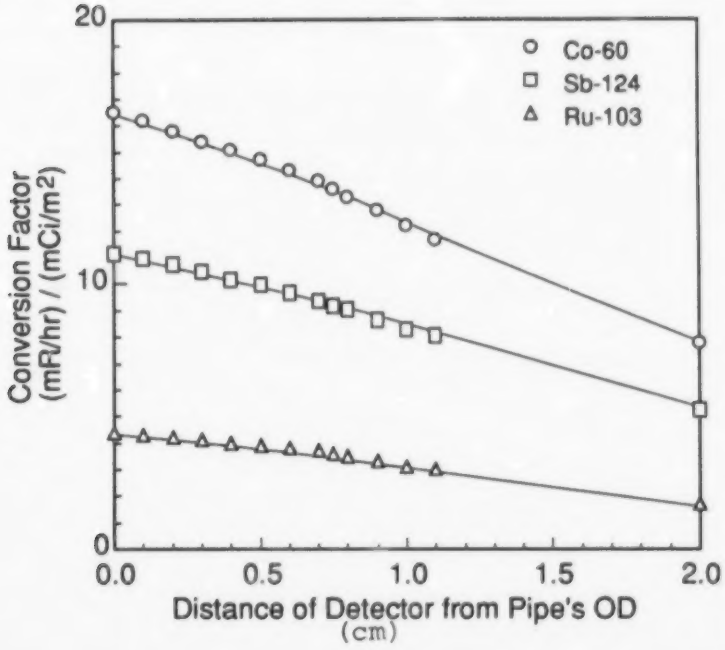


**Figure 5. Effect of Detector's Location on Calculated Conversion Factors (OD 7.68 cm & ID 6.27 cm )**

4.2 Decontamination Behaviour of Co-60 and Sb-124

Co-60 as expected was the principal source of activity prior to the decontamination. In addition and present to varying extents were the isotopes Ru-103, Zr/Nb-95, Fe-59, La-140 and Sb-124. At the end of the 1st CAN-DECON, Co-60 particularly on the inlet feeders was significantly lower, Sb-124 particularly on the outlet feeders had increased markedly while the other isotopes were all but eliminated. The decontamination factors for Co-60 in the 1st CAN-DECON step and the overall 3 steps are given in Table 5.

**TABLE 5**

**DECONTAMINATION FACTOR FOR Co-60**

| Pipe | 1st R Step | ROR Steps |
|---|---|---|
| P21 (outlet) | 2.6 | 12.6 |
| P1 (outlet) | 1.8 | 4.9 |
| U5 (inlet) | - | 33 |
| T18 (inlet) | 38 | 67 |

The decontamination factors for Sb-124, taking into account its decay (60 d halflife) are given in Table 6. Note that during the 46 d period between the 1st CAN-DECON and the oxidizing step, reactor defuelling/draining activities led to a significant removal of previously deposited Sb-124 activity on P1 (on the contrary an increase in Co-60 activity was experienced). If the P1 Sb-124 DF for the combined OR steps is applicable to P21, then one may conclude that Sb-124 activity on outlet feeders generally decreased during the 46 d period. Invoking a similar argument, one could conclude that Sb-124 activity on inlet feeders increased as a result of defuelling/draining activities. These conclusions are necessarily speculative due to paucity of the data; however, an oxidizing environment could have existed during the said period and caused the antimony transport.

**TABLE 6**

**DECONTAMINATION FACTOR FOR Sb-124**

| Pipe | 1st R Step | D Step* | OR Steps | DOR Steps |
|---|---|---|---|---|
| P21 (outlet) | 0.15 | - | - | 1.76 |
| P1 (outlet) | 0.10 | 1.67 | 1.2 | 2.0 |
| U5 (inlet) | - | - | 1.3 | - |
| T18 (inlet) | 0.29 | - | - | 0.73 |

* Refers to the 46d period between the 1st CAN-DECON and the oxidizing step

The low Sb-124 DFs for the combined OR steps together with the constancy of Sb-124 peak counts in the feeder cabinet scans recorded during this phase of the decontamination indicate conclusively that a) no removal of Sb-124 occurred during the oxidizing step itself and 2) what little removal occurred was realized in the final CAN-DECON step which is in marked contrast to the behaviour of Sb-124 during the 1st CAN-DECON. It is worth noting that the observed inability of the AP step in effecting antimony removal is consistent with previously reported/6/ laboratory experience using contaminated CS coupons.

## 5.0 CONCLUSIONS AND RECOMMENDATIONS

A main outcome of this work is the demonstrated adequacy of the measurement technique for quantifying radioisotope activity on feeder pipes. Improvements to the technique should include 1) provision of an engineered system for installing Densalloy pipe shields; the latter in comparison to lead blankets would provide improved shielding against extraneous radiation entering from behind a pipe and 2) developing pipe efficiency curves spanning a wider range in photon energies and at additional intermediate distances.

Equipment set-up at the inlet feeders was very awkward. This along with the relatively high radiation fields in a feeder cabinet warrant an assessment of other locations such as at the reactor face or inside the vertical feeder cabinets. Performing measurements at these alternate locations may require the acquisition of a spectrometer with a vertically oriented detector housing.

Complementary measurements using the shielded gamma survey probes should continue in the future at least until suggested improvements in the spectrometric technique can be properly assessed. The probes should be replaced with those having a less pronounced energy dependence; the latter should be evaluated up to 1700 keV to include the response to Sb-124. In addition, precise location of the detectors within their shielding cavities must be known.

Examination of the Sb-124 data has confirmed the previously noted ineffectiveness of alkaline permanganate in decontaminating Sb-124 present on carbon steel surfaces. This warrants a re-examination of process options should Sb-124 removal be crucial in future decontaminations.

## 6.0 ACKNOWLEDGEMENTS

The contributions of J.P. Krasznai, D. Beaudry, B. Aucoin, C.E. Breckenridge and D. Mueller in performing the measurements are gratefully acknowledged. The shielded gamma survey probe measurements were provided by J. Lamarre (CPSD) while conversion factor calculations were performed by R. Monteforte and C.A. Morrison (D&D-Gen). Their co-operation is appreciated.

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## APPENDIX


| | |
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| Figure A.1 | Details of Densalloy Shield |
| Figure A.2 | Point Source Efficiency of Detector |
| Table A.1 | Calculated Attenuation Coefficients for Densalloy |
| Table A.2 | Summary of Counts/sec Outlet Feeder Pipe Scan Data (1.27 cm. collimator) |
| Table A.3 | Summary of Counts/sec Inlet Feeder Pipe Scan Data (1.27 cm Collimator) |

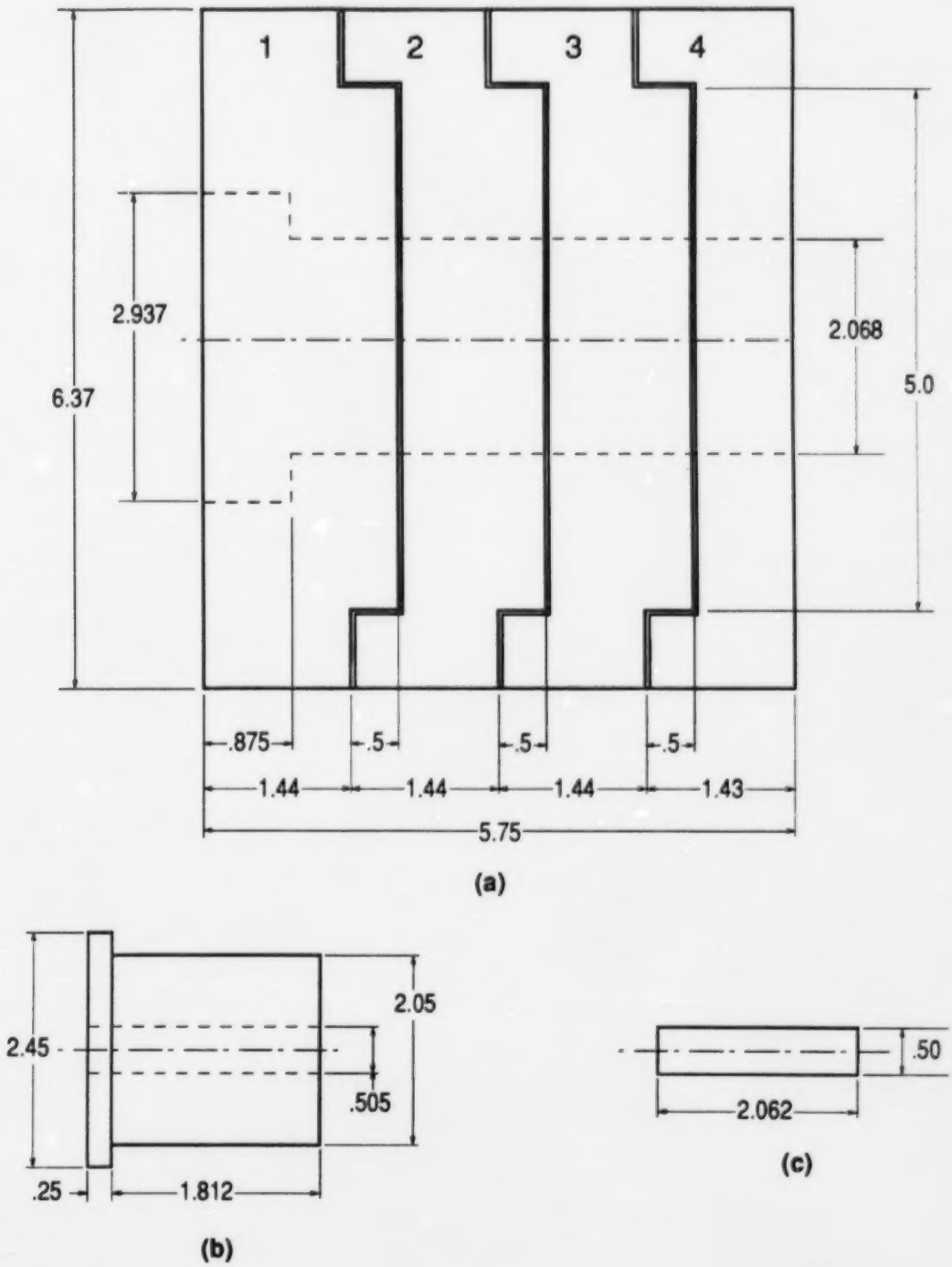


**Figure A.1. Schematic of (a) Annular Spectrometer Shield (b) Collimator and (c) Cylindrical plug**

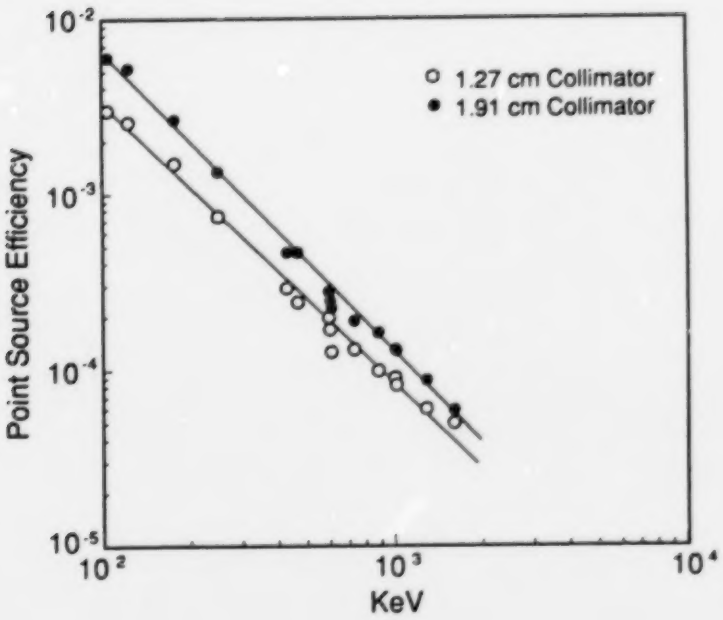


**Figure A.2. Point Source Efficiency of Detector (Source Placed on Face of Collimator)**

**TABLE A.1**

**CALCULATED ATTENUATION COEFFICIENTS FOR DENSALLOY/2/**

| MeV | 0.6 | 0.8 | 1.0 | 1.5 |
|---|---|---|---|---|
| $\mu(cm^{-1})$ | 1.849 | 1.392 | 1.156 | 0.883 |

Note: By interpolation, $\mu$ at 0.662, 1.173 and 1.332 MeV were calculated to be 1.71, 1.06 and 0.975 ($cm^{-1}$), respectively.

TABLE A.2
SUMMARY OF COUNTS/SEC OUTLET FEEDER PIPE SCAN DATA (1.27 CM COLLIMATOR)

| | | Outlet Feeder P21 | | | Outlet Feeder P1 | | | |
|---|---|---|---|---|---|---|---|---|
| Isotope | keV | Before R | After R | After ROR | Before R | After R | Before O | After ROR |
| Sb-125 | 427.9 | - | - | 0.193 ± 0.102 | - | - | 0.210 ± 0.187 | 0.203 ± 0.094 |
| Ru-103 | 497.1 | 2.008 ± 0.114 | 0.339 ± 0.151 | 0.009 ± 0.088 | 0.091 ± 0.161 | 0.892 ± 0.200 | 0.377 ± 0.185 | 0.153 ± 0.084 |
| Sb-124 | 602.7 | 0.392 ± 0.098 | 1.708 ± 0.155 | 0.618 ± 0.096 | 0.448 ± 0.146 | 2.379 ± 0.207 | 0.900 ± 0.194 | 0.501 ± 0.089 |
| Zr-95 | 724.2 | 0.413 ± 0.092 | - | 0.032 ± 0.076 | 0.602 ± 0.130 | - | - | 0.045 ± 0.072 |
| Nb-95 | 765.8 | 1.481 ± 0.092 | - | 0.037 ± 0.072 | 1.608 ± 0.150 | 0.139 ± 0.156 | 0.207 ± 0.156 | 0.074 ± 0.070 |
| Mn-54 | 834.8 | 0.250 ± 0.080 | - | - | 0.257 ± 0.132 | - | - | - |
| Fe-59 | 1099.2 | 0.311 ± 0.061 | - | - | 0.274 ± 0.112 | - | - | - |
| Co-60 | 1173.2 | 3.369 ± 0.147 | 1.065 ± 0.105 | 0.260 ± 0.060 | 2.606 ± 0.120 | 1.660 ± 0.125 | 2.702 ± 0.143 | 0.567 ± 0.059 |
| Fe-59 | 1291.6 | 0.153 ± 0.056 | - | - | 0.124 ± 0.049 | - | - | - |
| Co-60 | 1332.5 | 3.397 ± 0.137 | 0.951 ± 0.102 | 0.253 ± 0.054 | 2.530 ± 0.112 | 1.536 ± 0.112 | 2.386 ± 0.115 | 0.489 ± 0.053 |
| La-140 | 1596.5 | 0.126 ± 0.031 | - | - | 0.219 ± 0.037 | - | - | - |
| Sb-124 | 1691.0 | 0.096 ± 0.029 | 0.345 ± 0.067 | 0.132 ± 0.036 | 0.054 ± 0.021 | 0.526 ± 0.061 | 0.165 ± 0.039 | 0.139 ± 0.028 |
| Pipe - Collimator Face Distance (cm) | | 22.2 | 33 | 24.1 | 22.9 | 18.0 | 18.4 | 23.0 |

TABLE A.3
SUMMARY OF COUNTS/SEC INLET FEEDER PIPE SCAN DATA (1.27 CM COLLIMATOR)

| | | Inlet Feeder U5 | | | Inlet Feeder T18 | | |
|---|---|---|---|---|---|---|---|
| Isotope | keV | Before R | Before O | After ROR | Before R | After R | After ROR |
| Sb-125 | 427.9 | - | 0.239 ± 0.251 | 0.122 ± 0.169 | - | - | 0.230 ± 0.127 |
| Ru-103 | 497.1 | - | 0.277 ± 0.248 | 0.075 ± 0.151 | 1.830 ± 0.513 | 0.061 ± 0.180 | 0.063 ± 0.110 |
| Sb-124 | 602.7 | - | 0.810 ± 0.262 | 0.434 ± 0.157 | - | 1.166 ± 0.192 | 0.814 ± 0.120 |
| Zr-95 | 724.2 | 0.685 ± 0.251 | 0.139 ± 0.200 | 0.006 ± 0.137 | 0.117 ± 0.362 | - | 0.029 ± 0.098 |
| Zr-95 | 756.7 | 0.790 ± 0.431 | - | - | - | - | - |
| Nb-95 | 765.8 | 2.728 ± 0.418 | 0.670 ± 0.216 | 0.055 ± 0.131 | 3.140 ± 0.460 | - | 0.062 ± 0.094 |
| Mn-54 | 834.8 | 0.324 ± 0.372 | - | - | 0.357 ± 0.338 | - | - |
| Fe-59 | 1099.2 | 0.274 ± 0.322 | - | - | 0.781 ± 0.307 | - | - |
| Co-60 | 1173.2 | 10.090 ± 0.359 | 2.392 ± 0.193 | 0.367 ± 0.109 | 28.303 ± 0.360 | 0.683 ± 0.129 | 0.356 ± 0.075 |
| Fe-59 | 1291.6 | 0.127 ± 0.113 | - | - | 0.375 ± 0.106 | - | - |
| Co-60 | 1332.5 | 8.777 ± 0.334 | 2.068 ± 0.156 | 0.326 ± 0.100 | 26.169 ± 0.315 | 0.709 ± 0.123 | 0.413 ± 0.070 |
| La-140 | 1596.5 | 0.103 ± 0.069 | - | - | 0.281 ± 0.055 | - | - |
| Sb-124 | 1691.0 | 0.004 ± 0.041 | 0.165 ± 0.050 | 0.146 ± 0.035 | 0.092 ± 0.038 | 0.277 ± 0.076 | 0.239 ± 0.043 |
| Pipe - Collimator Face Distance (cm) | | 40.6 | 37.5 | 33.0 | 22.2 | 24.2 | 22.9 |

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